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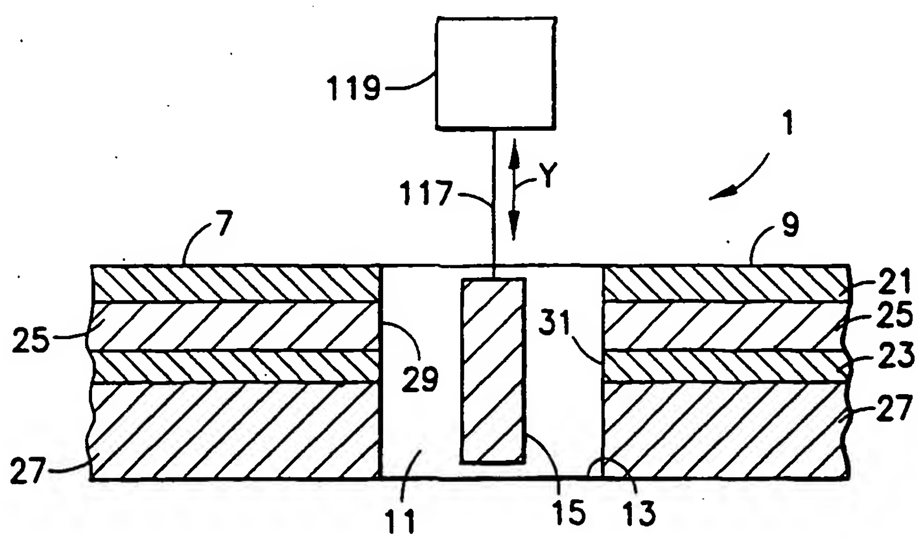
(54) Title: TUNABLE FABRY-PEROT FILTER HAVING A MOVABLE TUNING ELEMENT



(57) Abstract: A tunable filter which filters an optical signal passing therethrough includes a first waveguide (7) having a core (25) defining an optical path through the first waveguide and a partially-reflective first facet (29), and a second waveguide (9) having a core (25) defining an optical path through the second waveguide and that is coaxial with the first waveguide optical path and a partially-reflective second facet (31), the first and the second waveguides being separated from each other by a trench (11) defined therebetween, the first and second facets defining a Fabry-Perot cavity therebetween. A tuning element (15) is disposed in the trench between the first and second waveguides and can be selectively moved between a first position and at least a second position so that the optical length of the Fabry-Perot cavity is changed. The tuning element (15) may be caused to move by an actuator (119), such as an electrothermal actuator or electrostatic actuator.

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TUNABLE FABRY-PEROT FILTER HAVING A MOVABLE TUNING ELEMENT

FIELD OF THE INVENTION

The present invention is directed to a tunable Fabry-Perot optical filter.

BACKGROUND OF THE INVENTION

In optical transmission, it may be desirable to filter an optical signal to eliminate all but a desired wavelength of light.

To increase versatility, it is desirable that the filter used to extract the wavelength of interest be tunable. This way, if the wavelength of interest changes, the filter can be retuned to that wavelength. Such retuning avoids the need to use multiple filters, or to replace an existing single-wavelength filter corresponding to a given wavelength with a single-wavelength filter corresponding to a different wavelength.

It also may be desirable to reshape optical signals composed of multiple wavelengths of light. Such reshaping involves altering the spectrum of different wavelengths contained in the optical signal. For example, an optical signal made up of equal amounts (on a power basis) of three different wavelengths of light could be reshaped so that the amount (on a power basis) of one of those wavelengths is halved.

SUMMARY OF THE INVENTION

The present invention is directed to a filter having a Fabry-Perot cavity and a tuner disposed therein.

This invention involves tunable Fabry-Perot filters. These Fabry-Perot filters can be tuned to change the wavelength at which optical signals are filtered. Tuning is accomplished

by providing a tuner having a movable tuning element having a particular index of refraction , and which can be shifted into and out of a Fabry-Perot cavity. This way, the Fabry-Perot cavity will have different optical lengths depending upon whether or not the tuning element is positioned in the Fabry-Perot cavity, and so the filtering behavior of the Fabry-Perot filter will vary accordingly.

In some cases it may be desirable to employ a constant tuning element, and in others, a variable tuning element. Successive Fabry-Perot cavities containing either the same or different types (constant/variable) of tuning elements be provided.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts which will be exemplified in the disclosure herein. The scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawing figures, which are not to scale, and which are merely illustrative, and wherein like reference characters denote similar elements throughout the several views:

FIG. 1A is a schematic view of a Fabry-Perot filter having a movable constant tuning element constructed in accordance with an embodiment of the present invention;

FIG. 1B is a schematic view of a Fabry-Perot filter having a movable variable tuning element constructed in accordance with another embodiment of the present invention;

FIG. 2 is a schematic view of a Fabry-Perot filter having two movable constant tuning elements constructed in accordance with a further embodiment of the present invention;

FIG. 3 is a cross-sectional side view taken along line 3-3 of the optical tuner of FIG. 1, and of one of the optical tuners of FIG. 2;

FIG. 4 is a cross-sectional side view taken of an alternative embodiment of the optical tuner and depicting a second direction of movement of the tuning element;

FIG. 5A is a perspective view of a constant tuning element;

FIG. 5B is a perspective view of a variable tuning element;

FIG. 6A is a top plan view of an embodiment of a stepped variable tuning element;

FIG. 6B is an elevational view of the stepped variable tuning element taken along line 6-6 of FIG. 6A;

FIG. 6C is a top plan view of another embodiment of a stepped variable tuning element;

FIGS 7A and 7B are top plan views showing a variable tuning element in two different positions;

FIG. 8 is a top plan view of a light beam passing through a variable tuning element as depicted in FIGS. 1B and 5B;

FIG. 9 is a partial cross-sectional schematic view of an electrothermal actuator in accordance with an embodiment of the present invention;

FIGS. 10 and 11 are schematic views of two embodiments of electrostatic actuators in accordance with embodiments of the present invention;

FIG. 12 is a cross-sectional view of a waveguide taken along line 9-9 of FIG. 1A and constructed in accordance with an embodiment of the present invention;

FIGS. 13A and 13B show the relationship between beam diffraction and trench length for light passing across a trench between waveguides;

FIGS. 14 and 15 are schematic views showing exemplary ways to reduce diffraction of light passing across a trench;

FIG. 16 is a schematic view showing offset waveguides arranged about a tuning element; and

FIGS. 17A and 17B depict the assembly of an optical switch in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The present invention is directed to a Fabry-Perot filter including at least one of a constant tuner or a variable tuner, and which change the output wavelengths for the Fabry-Perot filter.

As used herein, the terms "light signal" and "optical signal" are used interchangeably, and may include signals such as WDM, DWDM, UDWDM signals, and the like, for example. The terms "light", "light signal" and optical signal" are intended to be broadly construed and to refer to visible, infrared, ultraviolet light, and the like.

This invention provides for and encompasses both constant tuners and variable tuners. Constant tuners alter the optical length of a Fabry-Perot cavity by a predetermined and fixed amount, whereas variable tuners can change the optical length of the Fabry-Perot cavity by a range of different lengths.

The tuners disclosed herein share a common configuration according to which light carried by a waveguide passes through a tuning element as the light crosses between waveguides, for example, crossing a trench defined between two waveguides. The tuning element is constructed from material having an index of refraction different from the index of refraction of the medium between the waveguides. That element is selectively caused to move into and out of the trench between two waveguides (i.e., into and out of an optical signal path defined by and between two waveguides) so as to alter the optical length between the waveguides.

Referring next to the drawings in detail, and with initial reference to FIG. 1A, a Fabry-Perot cavity 2 is formed between input waveguide 7 and output waveguide 9. More specifically, input waveguide 7 has a flat output facet 29, and output waveguide 9 has a flat input facet 31. Because the output and input facets 29, 31 are coaxial and parallel to one another, a Fabry-Perot cavity 2 is formed therebetween.

The two facets 29, 31 have partial reflecting surfaces, which thereby form the Fabry-Perot cavity 2. The partial reflecting nature of facets 29, 31 can be due to either inherent material properties or a thin film coating.

The Q factor of the Fabry-Perot cavity 2 can be controlled by changing the cavity length and/or the facet reflectivity.

Fabry-Perot cavity 2 will, in a known manner, serve to filter light passing therethrough on the basis of the light's wavelength. It is known that the maximum output of the Fabry-Perot cavity 2 occurs when the cavity's length L_c is: $\left(\frac{N}{2}\right)\lambda$, N being an integer and λ being the wavelength of the light passing through the Fabry-Perot cavity 2. This also means that the output of the Fabry-Perot cavity 2 is a function of the cavity's optical length. The cavity's optical length L_o is the product of the cavity's actual length L_c and its refractive index *n*, that is, $L_o = L_c n$

Thus, altering the optical length of the Fabry-Perot cavity 2 will correspondingly change the wavelength of light for which the output of the Fabry-Perot cavity 2 will be maximized.

Since the optical length determined by both the cavity's actual length L_c and the index of refraction of the medium in the cavity, one or both of these parameters must be altered to change the wavelength of light output by the Fabry-Perot cavity 2.

The present invention tunes the Fabry-Perot filter by varying the optical length of the Fabry-Perot cavity 2. This is accomplished using a tuner to move a tuning element 15 into and out of the optical path in the Fabry-Perot cavity 2. The tuning element 15 has a different index of refraction than does the Fabry-Perot cavity 2, and so the Fabry-Perot cavity's index of refraction will vary according to where the tuning element 15 is located in the Fabry-Perot cavity 2, changing the refractive index of cavity 2.

More specifically, and with reference to FIG. 1A, a constant tuner according to an embodiment of the present invention is there depicted and generally designated by reference numeral 3. That tuner 3 incorporates a tuning element 15 that introduces a generally constant

change in optical length of the path between input and output waveguides 7, 9. As shown in FIGS. 1A, 3 and 5A, the tuning element 15 may be substantially planar with parallel planar walls, and is preferably oriented with its longitudinal length, *l*, oriented perpendicular to an optical path indicated by line X and defined by the optical paths of input and output waveguides 7, 9. The amount by which the phase of the optical signal is shifted can be controlled by selection of a material and/or dimensions for the tuning element 15 having a desired index of refraction (which is an inherent property of the material) and fabricating the element 15 to a particular thickness *t*.

It should be understood that the tuning element 15, because of its particular index of refraction, slows or speeds the optical signal passing therethrough. This slowing or speeding has the effect of lengthening or shortening the Fabry-Perot cavity 2. Such a change in the optical signal also can be considered a phase shift because the phase of the optical signal, owing to its speeding or slowing, is changed relative to what would be the phase of the optical signal had it not been shifted.

In a first embodiment of the present invention, and with reference to FIGS. 1A and 3, a Fabry-Perot filter 1 includes input waveguide 7 and output waveguide 9 formed on a silicon-based substrate 27 (by way of example only, a quartz substrate also could be used) and which has a core 25 sandwiched between a bottom cladding 23 and a top cladding 21. The input waveguide 7 and output waveguide 9 may be either photonic-wire or photonic-well waveguides and are separated from each other by a trench 11 defined at least partially in the substrate 13. A movable tuning element 15 is disposed in the trench 11 and may be selectively caused to move along the trench 11 and into and out of the optical path, which is generally defined by the input and output waveguide cores 25 and along the longitudinal axes of the input and output waveguides 7, 9. The tuning element 15 may be caused to move in a direction generally indicated by arrow Z by an actuator 19 such as, for example, an electrothermal actuator 219 (see, e.g., FIG. 9) or electrostatic actuator 319 or 419 (see, e.g., FIGS. 10 and 11) coupled to the tuning element 15 by a relatively rigid yet lightweight link 17. Link 57 is preferably made from a light-weight, stiff material.

Again, the output wavelength of the Fabry-Perot cavity 2 will be determined by the position of the tuning element 15 in the trench 11 running through that Fabry-Perot cavity 2. The Fabry-Perot cavity 2 will have one output wavelength when the tuning element 15 is positioned between waveguides 7, 9 in the optical path, and another when that tuning element 15 is disposed outside that optical path and not between waveguides 7, 9. This arrangement provides a two-state Fabry-Perot filter in which the wavelength of the output optical signal can have one of two different values.

A further embodiment of this invention is the Fabry-Perot filter 201 depicted in FIG. 2. This Fabry-Perot filter differs from the Fabry-Perot filter 1 previously discussed in that two tuners 203, 203', which as depicted may be similar in construction, are provided in series along the optical path. In this Fabry-Perot filter 201, light enters the filter through input waveguide 7, passes through the Fabry-Perot cavity 2, leaves that cavity and enters a bridge waveguide 6, leaves that bridge waveguide 6 and enters another Fabry-Perot cavity 2', and then leaves that cavity through output waveguide 7. It will be appreciated that the number of Fabry-Perot cavities 2, 2' is only exemplary and not limiting; any number of successive filters could be provided, or filter 203 may be constant filter and filter 203' may be a variable filter, as discussed below, or vice versa.

This arrangement of successive Fabry-Perot cavities filters 2, 2' may be preferable because the each of the successive Fabry-Perot filters 2, 2' can be tuned to a different wavelength. In that case, the Fabry-Perot filter 201 would be able to filter out a range of different wavelengths of light. Additionally, spectral reshaping of the input optical signal may be possible if several of the Fabry-Perot cavities 2, 2' are tuned to filter different wavelengths of light.

The present invention is particularly applicable to waveguides which are formed on integral planar optical substrates. Generally speaking, an integrated planar optical substrate refers to a relatively flat member having a supporting substrate and a number of layers of different materials formed thereon. The substrate and the different materials have particular optical qualities such that optically useful structures such as waveguides can be formed on the

supporting substrate by suitable shaping or other processing (e.g., reactive-ion etching or other suitable semiconductor etching processes).

With continued reference to FIG. 3, and additional reference to FIG. 12, the waveguides 7, 9 of the present each have a buried core 25 having a thickness, t_c, which ranges from approximately 3-15 μm, and a height, h_c, ranging from approximately 3-10 μm. More preferably, the core thickness can range from approximately 6 to 14 μm, and the core height from approximately 6 to 8 μm. The core 25 is preferably square.

The upper and lower cladding layers 21, 23 adjacent to core layer 25 can each be approximately 3-18 μm thick, and are preferably each approximately 15 μm thick.

While a wide variety of materials can be used to make the core and cladding layers, silica is presently preferred.

The tuning element 15 is preferably rectangular and can be from approximately 1-8 μm thick, approximately 10-100 μm high, and approximately 10-100 μm long. The tuning element 15 can be made from any sufficiently rigid and light material. Preferably, the tuning element is approximately 2 μm thick, approximately 30-40 μm high, and approximately 30-40 μm long, and made from silicon. By way of non-limiting example, other materials such as polymers or dielectric films also could be used.

The present invention will work with both weakly-confined waveguides and strongly-confined waveguides. Presently, use with weakly-confined waveguides is preferred.

Waveguides 7, 9 can be formed from a wide variety of materials chosen to provide the desired optical properties. While silica-based materials are preferable (e.g., SiO_2), other semiconductors that provide the desired optical properties may also be used. For example, the core 25 might include germanium oxide-doped silica deposited atop a silicon or quartz substrate 27, while the top and bottom cladding 21, 23 may include boron phosphide-doped silica glass. Other materials which could be used for the core 25 include, by way of non-limiting example, indium phosphide and gallium arsenide, and for the cladding 21, 23

include, indium phosphide, gallium arsenide, aluminum oxide, silicon nitride or polymers, or combinations thereof.

Referring again to FIG. 1A, the trench 11 is filled with a medium (not shown) having a refractive index that generally differs from the refractive indices of the waveguides 7, 9 and tuning element 15 (the refractive index of the element 15 also being different from that of the waveguides 7, 9, which can be substantially the same). That medium may include air or a vacuum, by way of non-limiting example, and need not provide refractive index matching for the medium and waveguides 7, 9.

An optical signal propagating in and guided by the core 25 of input waveguide 7 exits that waveguide via an output facet 29, passes across the trench 11, and enters the output waveguide 9 through an input facet 31. If the tuning element 15 is located in the optical path X, the optical signal will pass through the element 15 which will alter the optical length of the path between waveguides 7, 9. The amount by which the optical length of the path changes is predetermined and depends on the thickness, *t*, of the element 15 and on the material from which the tuning element 15 is constructed, which determines its refractive index. If the tuning element 15 is not located in the optical path X, the optical length between the waveguides 7, 9 will not be changed.

It is desirable to minimize the spacing between waveguides 7, 9, so as to reduce the possibility of diffraction (spreading) of an optical signal as it passes between the waveguides 7, 9 (see, e.g., FIGS. 13A and 13B). In part, this can be done by providing a trench 11 having a width just slightly greater than the thickness *t* of the tuning element 15.

Another way to reduce optical losses in the system is to apply an antireflective coating (not shown) to the waveguide facets 29, 31.

The tuning element 15 depicted in FIG. 1A is a constant tuning element in that it has a relatively constant thickness *t* and thus changes by a fixed amount the optical length of the Fabry-Perot cavity between waveguides 7, 9, regardless of the point on the tuning element 15 at which the optical signal enters and exits the element 15. Generally, a tuning element 15 is a transparent piece of material having certain optical properties, in particular, a refractive

index different from that of the medium surrounding the element 15 and different from that of the waveguides 7, 9. As light encounters different refractive indices, (i.e., passes through different optical materials or between optical elements (waveguides, waveguide/resonator, etc.), the light may change speed and experience a resultant change in phase relative to light not passing through such material or between such elements. The tuning element 15 is preferably a generally rectangular prism having an input surface 2 and an output surface 4 (see, .e.g., FIG. 3) which are generally parallel with each other. As depicted in FIG. 5A, the tuning element 15 has a thickness, *t*, that thickness being chosen to provide a desired and fixed change in optical length of the Fabry-Perot cavity 2 between the input and output waveguides 7, 9. The tuning element 15 need only be extended into the optical path enough to ensure that an optical signal passing from waveguide 7 to waveguide 9 completely passes through the element 15. The height of the tuning element 15 may be h. The length of the tuning element 15 does not affect its optical path-changing characteristics, and is preferably sized so as to minimize the amount of movement required to cause the element 15 to move into and out of the optical path X. Other than inducing a change in the optical length of the Fabry-Perot cavity between the input and output waveguides, 7, 9, the material from which the tuning element 15 is constructed should not significantly alter (e.g., absorb) the characteristics of the optical signal which passes therethrough.

As shown in FIG. 1A, the tuning element 15 is coupled to actuator 19 by a stiff yet light link 17, and is sized and shaped to move reciprocally as generally indicated by arrow Z and without interference in trench 11. The actuator 19 can then be used to move the tuning element 15 between a first position, in which the element 15 is located in the optical path X (as depicted in FIGS. 1A and 3), and a second position, in which the element 15 is out of the optical path X (not shown). The optical length of the Fabry-Perot cavity 2 is therefore only changed when the tuning element 15 is in the first position, and not when the tuning element 15 is in the second position.

Actuator 19 serves to move the tuning element 15 into and out of the optical path. While any suitable actuator could be used to implement this invention, it is presently thought that either an electrothermal or electromechanical type actuator is preferred.

Electrothermal actuators are in general known in the art, and therefore will not be described in precise detail. For the purposes of the present invention, it will be appreciated that any electrothermal actuator could be used which changes its size in response to the application of thermal energy enough to cause the desired movement of element 15 between the first and second positions. One benefit to using electrothermal actuators is that such actuators may be latching-type devices which maintain its position without the continuous application of energy. Thus, a latching-type actuator will remain in either one of two positions until it is caused to switch out of that position.

An illustrative electrothermal latching-type actuator 219 suitable for use with the present invention is depicted in FIG.9. That actuator 219 includes a flexible member 45 which is securely fixed at endpoints 49, 49' to the walls of a cavity 54 defined with an actuator housing 51. Cavity 54 is sized and shaped to allow movement of flexible member 45 sufficient to cause the tuning element 15 to move between the first and second positions. Also provided is a heater 47, which is located in relatively close proximity with the member 45. When the heater 47 is driven (i.e., caused to heat), the member 45 warms and expands. Since the member's ends are secured at endpoints 49, 49', the member 45 cannot simply expand so that the endpoints 49, 49' shift outward. Instead, compressive stresses will be generated along the member's length. These stresses increase until they reach a level sufficient to cause the member 45 to change its position from that indicated by reference character A to that indicated by reference character B in FIG. 9, i.e., into and out of the first and second (or second and first) positions. Alternatively, member 45 could itself be the heater.

In an alternative embodiment, and with reference to FIG. 10, an electrostatic actuator 319 may also be used to selectively move tuning element 15. Benefits of electrostatic actuators include high operating speed, low energy consumption, and minimal system

heating. One type of electrostatic actuator 319 usable in connection with the present invention is depicted in FIG. 10. That actuator 319 includes electrodes 55, 55' located on opposite sides of a piezoelectric element 53 made from a material which expands and contracts in at least one dimension (i.e., width or length) when an electric field is applied to the electrodes 55, 55'. Piezoelectric element 53 may thus be caused to expand and contract in the direction indicated by arrow Z, imparting movement to the tuning element 15.

It is possible that one actuator alone may not be sufficient to provide the required amount of movement for the element 15. This can be rectified by providing a piezoelectric actuator 419 having a number of interlaced fingers 59, such as that depicted in FIG. 11. These fingers 59 are attached to a support 57 within actuator 419, which serves to secure the base of the fingers 59. When an electrical signal is applied to electrodes (not shown), the total displacement in the direction of arrow Z of endpoint 60 will reflect the cumulative displacement of all of the fingers 59. Since the displacement of endpoint 60 is the sum of the fingers' individual displacements, a significant movement of the element 15 can be achieved. This type of electrostatic actuator 419 may require the application of substantial voltage, possibly on the order of 100 V, to obtain the desired movement of the element 15. Despite the magnitude of this voltage potential, very little power is required, since the current flow through the electrostatic actuator 419 is negligible.

It should be understood that the direction of motion of the tuning element 15 is not limited to movement along the trench 11. Tuning element 15 could be moved in any other direction which guides it into and out of the path of light passing between the waveguides 7, 9, so long as the tuning element 15 can move into and out of the first and second positions as defined herein. As shown in FIG. 4, tuning element 15 may be caused to move in a direction generally upward, i.e., in the direction of arrow Y, along a line normal to the plane in which waveguides 7, 9 lie, or similarly, along a diagonal line intersecting that plane.

The width of the trench 11 between the input waveguide 7 and the output waveguide 9 is preferably minimized to reduce diffraction, which is the undesirable spreading of light as it travels unconfined. There may be diffraction of the optical signal (i.e., light beam) each time

it passes between the waveguides 7, 9. Owing to this diffraction, the light beam ultimately output from the tuner 3, 103 may be somewhat larger in area than the original incident beam of light as it first enters the Fabry-Perot filter 1.

Depending upon the particulars of a given installation, it may or may not be necessary to compensate for this diffraction. There are several different ways to do this.

FIGS. 13A and 13B illustrate the effect of trench width upon diffraction losses. It can be seen in these drawings that as the trench width increases, the light's diffraction likewise increases. Since the light becomes more diffuse as the trench width increases, less of the original signal from waveguide 7 enters the waveguide 9. It is therefore preferable for the ends of the waveguides 7, 9 to be separated by as short a distance as is feasible, i.e., that the trench width be minimized.

There are several ways to control diffraction of the light as it crosses the trench 11. Diffraction can be controlled by separating the facets 29, 31 of waveguides 7, 9 by a distance only slightly greater than the widest point on the tuning element 15. With reference to FIGS. 1A and 3, waveguides 7, 9 are separated by and disposed around trench 11, and are preferably arranged in a coaxial manner about the same optical path defined by their respective cores 25. So that the waveguides 7, 9 will be separated by a distance insufficient to affect the transmission characteristics of an optical signal propagating from waveguide 7 across trench 19 to waveguide 9, trench 11 should be as narrow as possible to minimize light diffraction losses in the trench 11. Trench widths on the order of 10-35 μm are presently thought to be preferable.

At the same time there are factors which limit how narrow a trench 11 may be. A narrow trench 11 may complicate aligning the facing waveguides 7, 9, and may not be able to accommodate a tuning element of width sufficient to apply the maximum desired change in optical length of the Fabry-Perot cavity 2 for the tuning range of interest.

As depicted in FIG. 14, diffraction losses in wider trenches can be reduced by increasing the waveguide widths using tapers 71, 73. Tapers 71, 73 could be integral parts of waveguides 7, 9, or could be separate components attached thereto.

If desired, only one taper could be used on the output waveguide 9. In this arrangement (not shown), light would travel through input waveguide 7, pass through facet 29 into trench 11, and from trench 11 enter into taper 73 and from there enter output waveguide 9.

With reference to FIG. 15, the input waveguide 7 can be provided with a lens 75 facing trench 11. Lens 75 shapes light passing from that waveguide 7 before it crosses trench 11. While such a lens 75 could be formed in a variety of ways, an etched lens is now thought to be preferred.

It also may desirable for the trench 11 to be inclined relative to the axis along which the waveguides 7, 9, are arranged (not shown). Preferably the trench 11 is inclined relative to that axis at an angle of between 4°-8°, and more preferably, between 5°-7°, and most preferably, 6°. This geometry prevents light reflecting off the tuning element 3 from being directed back along the input waveguide 7.

In addition to a constant tuning element 3 along the lines of the foregoing embodiment, as discussed above and with reference to FIG. 1A, the present invention is also directed to a Fabry-Perot filter 101 using a tuner 103 having a variable tuning element 115, such as depicted in FIGS. 1B and 5B, and discussed in detail below. Since the overall index of refraction of the Fabry-Perot cavity 2 is determined by the amount (width) of the tuning element 115 disposed between the waveguides 7, 9, an element 115 having a variable thickness may be used to selectively vary the output wavelength of the Fabry-Perot cavity 2. The variable tuner 103 differs from the constant tuner primarily with regard to the shape of the tuning element 115; generally tapered versus generally rectangular.

As shown in FIGS. 1A and 5B, tapered tuning element 115 is generally tapered or wedge-shaped. That shape provides a range of different phase shifts, and as a result, different optical path lengths from approximately zero to some maximum amount found either before or at the widest part of the tuning element 115 at the end 34 opposite the tip 33, depending upon the position of the element 115 with respect to the waveguides 7, 9. Alternatively, the orientation of the tuning element could be reversed (not shown), s that the tuning element's

tip 33 is attached via link 17 to actuator 19. For that embodiment, consideration of the stress experienced by the tip 33, link 17, and actuator 34 may be necessary.

It should be understood that variable tuner 103 could be used in place of one or both of the constant tuners 203, 203' used in the Fabry-Perot filter 201 depicted in FIG. 2. Moreover, constant and variable tuners could be mixed in the Fabry-Perot filter in any order (not shown).

A variable tuner 103 may require a more precise actuator 19 than a constant tuner 3. The actuator 19 used in a constant tuner need only move the tuning element 15 between one of two positions (into or out of position between the waveguides 7, 9). As long as the element 15 is positioned in the optical path, optical length of the Fabry-Perot cavity 2 will be changed. For a variable tuner 101, the actuator 19 must move the variable tuning element 115 from position out of the optical path to a particular and relatively precise position in the optical path so that a particular thickness of the tuning element 115 will lie in the Fabry-Perot cavity 2 in the path of the optical signal, and so change the optical length of the Fabry-Perot cavity to the desired value, tuning the Fabry-Perot cavity 2 to the wavelength of interest.

One alternative to a more accurate actuator 119 is a more gradually sloping tuning element 115. For example, halving the tuning element's taper will double the distance by which the tuning element 115 would have to be moved to cause the same change in the optical length of the Fabry-Perot cavity 2.

The tapered sides 35, 37 of the tuning element 115 may cause an optical signal to experience a non-uniform phase shift over the width of the optical signal light beam 152 (see, e.g., FIGS. 5B and 8). Since the amount of phase shift introduced into the optical signal depends, at least in part, upon the thickness of the tuning element 115, the light beam will encounter varying thicknesses simply because the light beam has a finite width. Consequently, a part 83 of the light beam 152 encountering a wider part of the tuning element 115 will experience a greater phase shift than a part 81 of the light beam 152 encountering a narrower part. If the width of the light beam 152 is relatively small in comparison to the length of the tuning element 115, the difference in phase experienced at the outer edges of the

light beam 152 (the outer edges of the light beam will experience the greatest difference in thickness of the element 115) may be too small to adversely effect further transmission of the optical signal and thus may not require correction/compensation. If, however, correction/compensation is desired, one way to reduce the difference in phase shift would be to use a very gradually tapered tuning element 115 so that the light beam 152 experiences relatively negligible difference in thickness of the element 115 over the width if the light beam 152 thus providing a more homogeneously phase shifted optical signal. This element 115 also would change the optical path length of the Fabry-Perot cavity 2 more homogeneously. Such a tuning element 115 could be capable of producing as wide a range of changes in the optical length of the Fabry-Perot cavity 2, and so tune that cavity to have as wide a range of output frequencies as a more sharply tapered tuning element, although more movement of the tuning element 115 would be required.

The tapered tuning element can have a width ranging from approximately submicron-size at the tip to 100 μm at the widest portion, and a height from approximately 10-100 μm. The tapered tuning element can be made from any sufficiently rigid and light material. Preferably, the tapered tuning element is triangular, has a tip width of approximately submicron size, a maximum width of 30-40 μm, a height of approximately 30-40 μm.

By way of non-limiting example, the aforementioned tuning elements could be made from silicon, polymers, metallic or dielectric materials.

A further aspect of this invention involves an alternative configuration for the variable tuner 215 which reduces the above-described non-linearities in the output light beam. In this embodiment, the tapered tuning element 115 is replaced by a stepped tuning element 215, as shown in FIGS. 6A and 6B. The stepped tuning element 215 consists of two or more different rectangular shift regions 43, 43', 43" having different thicknesses, t, t', t''. Since the change in optical path length of an optical signal passing through each shift region 43, 43', 43" is a function of the shift region's thickness, it will be understood that thicker shift regions introduce a greater change in the optical path length than thinner shift regions. Instead f

allowing an infinite range of changes in the optical length of the Fabry-Perot cavity 2, this arrangement provides for a discrete number of shifts.

The number of shifts in optical length of the Fabry-Perot cavity 2 possible using a stepped tuning element 215 as depicted in FIGS. 6A and 6B will correspond to the number of shift regions 43, 43', 43". For example, a six-step tuning element could provide shifts approximately equal to x_1, x_2, x_3, x_4, x_5, x_6 (it is not thought that more than ten steps would be needed) When configured as depicted in FIG. 6A, or alternatively, with the smallest thickness being located near the link 17, the stepped tuning element 215 provides monotonic shifting of the optical length of the Fabry-Perot cavity 2. Alternatively, non-monotonic shifting may also be provided, as a routine matter of design choice.

When viewed from one end, such as depicted in FIG. 6B, for example, the stepped tuning element 215 can be seen to have a number of shift regions 43, 43', 43" all arranged symmetrically about a common center plane 44 defined through the element 215. Alternatively, the stepped tuning element 315 may have a stepped side 48 and a flat side 46, as depicted in FIG. 6C. The flat side 46 may face either waveguide 7, 9.

Individual shift regions 43, 43', 43" of the stepped tuning element 215, 315 need not be arranged either symmetrically or with a common edge plane. For example, shift regions 43, 43', 43" could be arranged so that the most frequently used shift regions are adjacent to one another (not shown). This arrangement will reduce the distance by which the tuning element 215, 315 would have to be moved to place those most used shift regions in the optical path X. Since the tuning element 215, 315 has to be moved a shorter distance, the tuner's response time would be improved.

The stepped tuning element 215, 315 can be fabricated either as a single integral piece or an assembly of several suitably-aligned pieces adhered or bonded together. Fabricating a single integral piece may be preferable because that avoids the need to align precisely the assembled pieces, and also avoids deformations in the optical material which might be caused by the adhering or bonding of the several pieces.

Another benefit to using a stepped tuning element 215, 315 is that a less precise actuator 19 may be needed, since the minimum distance by which the tuning element 215, 315 will have to be shifted is approximately equal to the distance between the centers of two adjacent shift regions. Given that the shift regions 43, 43', 43" are themselves somewhat wider than the width of the light beam 152, the minimum amount by which the actuator 19 would move the tuning element 215, 315 would be somewhat greater than the width of the light beam 152.

To ensure that the light beam 152 does not simultaneously encounter two different, adjacent shift regions 43, 43', 43", the length of each region is preferably no less than the width of the waveguides 7, 9.

If a tapered tuning element 115 is used in tuner 101, light traveling along the input waveguide 7 will, as depicted in FIGS. 8 and 16, undergo a change in direction after passing through the tuning element 115. For example, FIG. 16 depicts one way that output waveguide 9 can be repositioned to compensate for the light's change in direction. It will be appreciated that the relative positions of the waveguides 7, 9 and the tuning element 115 can be altered according to the tuning element's shape.

The optical tuner 1, 101 of the present invention can be monolithically formed or assembled using a flip-chip manufacturing technique, the latter being generally depicted in FIGS. 17A and 17B. In flip-chip manufacturing, the waveguides 7 and 9 and trench 11 are monolithically formed on a first chip 65 using known semiconductor fabrication techniques and processes (e.g., deposition, etching, etc.). The tuning element 15, actuator 19 and spacers 69 are formed on a second chip 67. Prior to assembly, the two chips are oriented to face each other, and aligned so that corresponding parts (e.g., tuning element 15 and trench 11) of the chips oppose one another. Spacers 69 regulate the distance between chips 65 and 67 as they are joined, and keep the chips from being pressed too close together. They also can be used to insure that the chips are joined in proper registration. The chips are then joined in known fashion.

It should be understood that this invention is not intended to be limited to the angles, materials, shapes or sizes portrayed herein, save to the extent that such angles, materials, shapes or sizes are so limited by the express language of the claims.

Thus, while there have been shown and described and pointed out novel features of the present invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the disclosed invention may be made by those skilled in the art without departing from the spirit of the invention. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall there between. In particular, this invention should not be construed as being limited to the dimensions, proportions or arrangements disclosed herein.

CLAIMS

What is claimed is:

1. An optical filter for filtering an optical signal passing therethrough, comprising:

a first waveguide, having a first core defining an optical path through the first waveguide, and a partially-reflective first facet;

a second waveguide, having a second core defining an optical path through the second waveguide, said second core being coaxial with the first waveguide optical path, and said second waveguide having a partially-reflective second facet, the first and the second waveguides being separated from each other by a trench defined therebetween, the first and second facets defining a Fabry-Perot cavity therebetween, the Fabry-Perot cavity having an optical length;

a tuning element movably disposed in the trench to selectively between the first waveguide and the second waveguide and being selectively movable between a first position which does not affect the optical length of the Fabry-Perot cavity and at least a second position in which the tuning element alters the optical length of the Fabry-Perot cavity.

2. An optical filter according to claim 1, wherein the tuning element is selectively movable between a first position in which the optical signal passing from the first waveguide through the first facet into the trench passes through the tuning element, and a second position in which the optical signal does not pass through the tuning element.

3. An optical filter according to claim 1, further comprising an actuator which moves the tuning element,

wherein the first and second waveguides lie in a plane, and wherein the actuator causes the tuning element to move between the first and second positions along the trench in the plane.

4. An optical filter according to claim 1, wherein the first and second waveguides lie in a plane, and wherein the actuator causes the tuning element to move between the first and second positions along a line intersecting the plane.

5. An optical filter according to claim 1, wherein the tuning element has two substantially planar walls.

6. An optical filter according to claim 5, wherein the two substantially planar walls are substantially parallel and wherein the tuning element introduces a substantially constant change in the optical length of the Fabry-Perot cavity.

7. An optical filter according to claim 5, wherein the two substantially planar walls converge toward one another, and wherein the tuning element has a length and a width that varies along the length, the second position being any position along the length and wherein a change in the optical length of the Fabry-Perot cavity caused by the position of the tuning element is determined by the width of the tuning element.

8. An optical filter according to claim 1, wherein the tuning element has a stepped profile.

9. An optical filter according to claim 8, wherein the tuning element has the stepped profile on both sides.

10. An optical filter according to claim 8, wherein the tuning element has the stepped profile on one side.

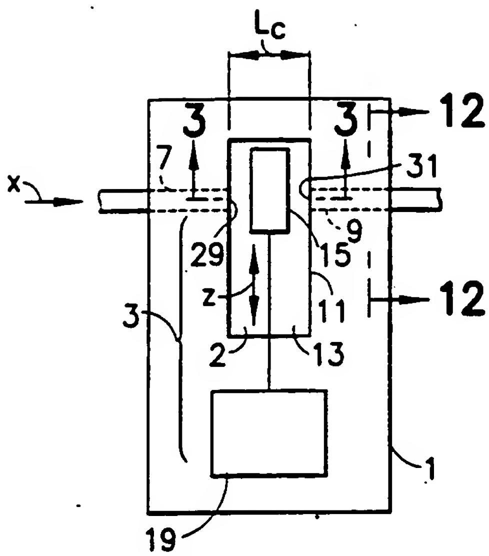

FIG.1A

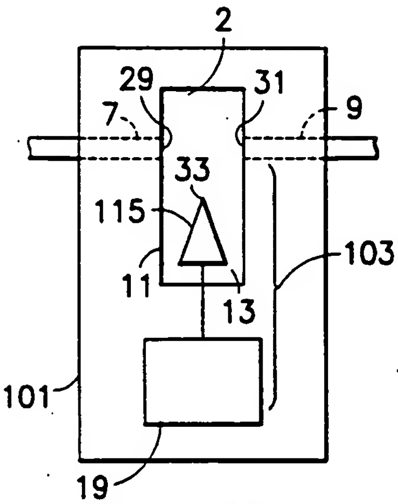

FIG.1B

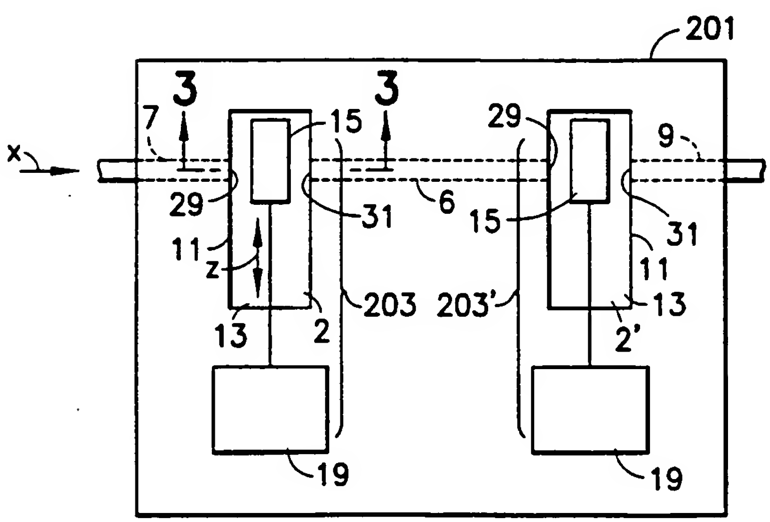

FIG.2

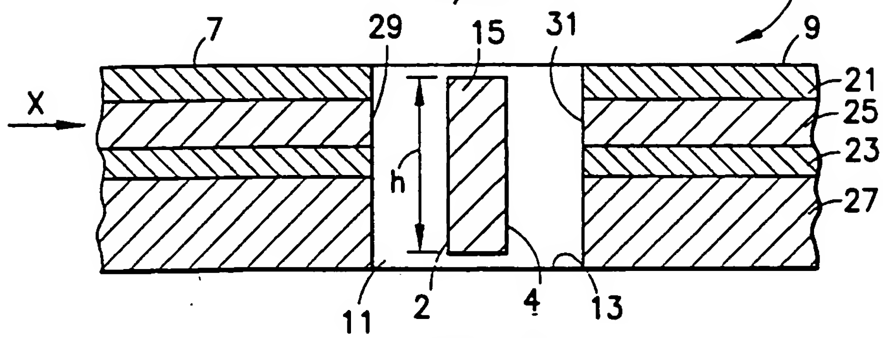

FIG.3

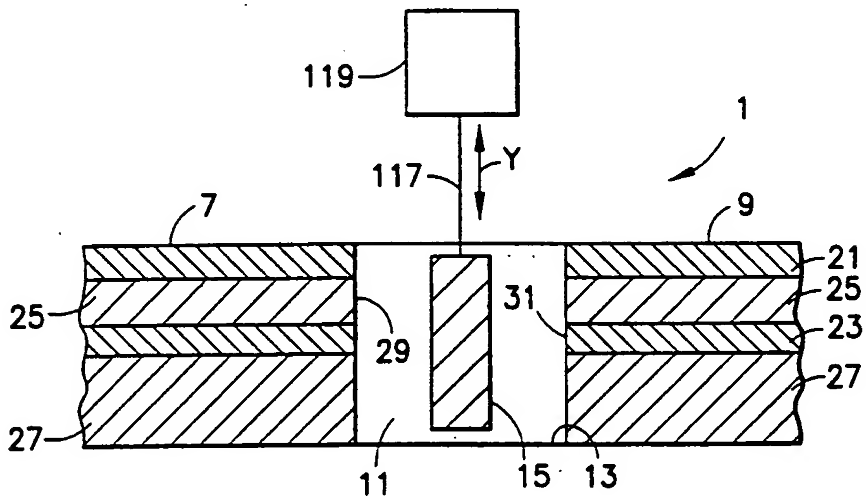

FIG.4

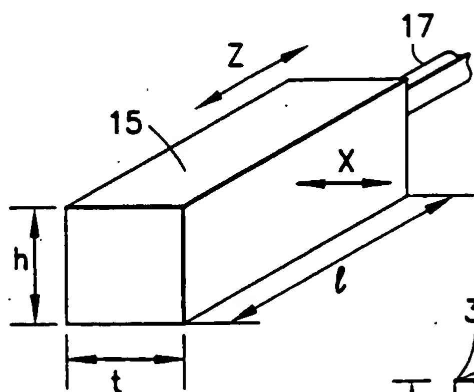

FIG.5A

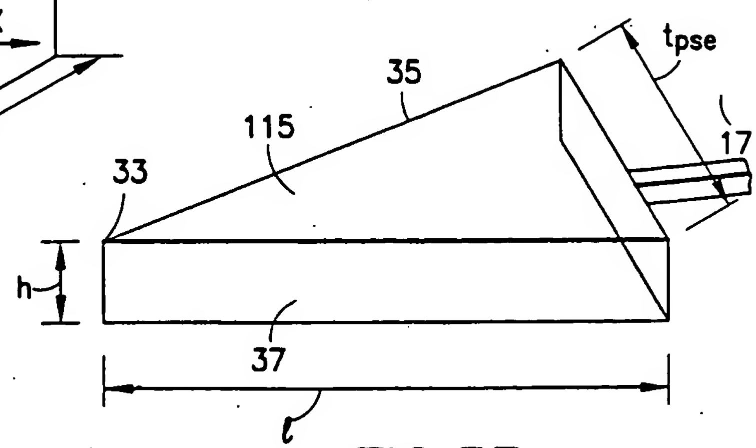

FIG.5B

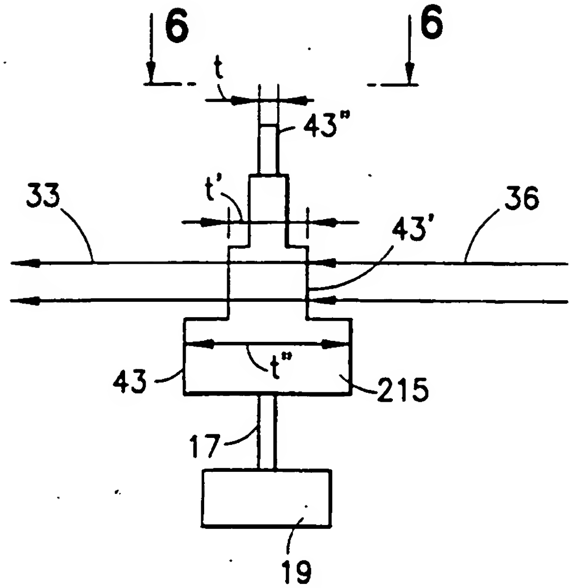

FIG.6A

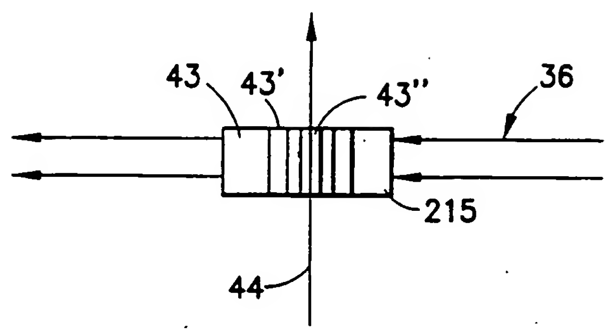

FIG.6B

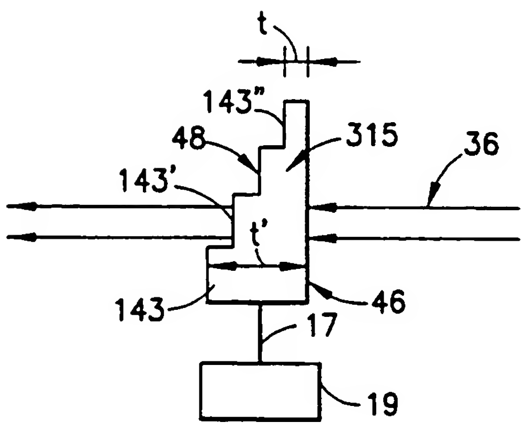

FIG.6C

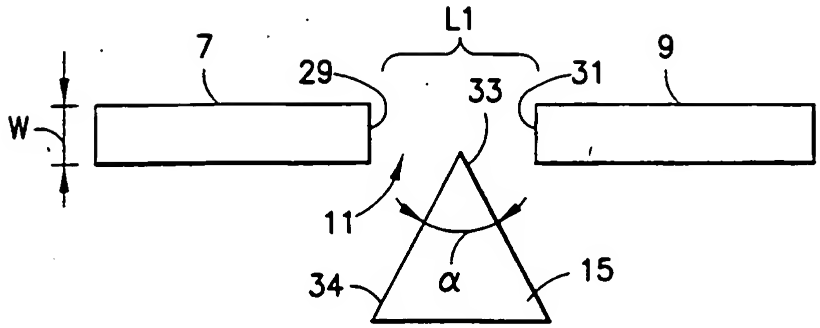

FIG.7A

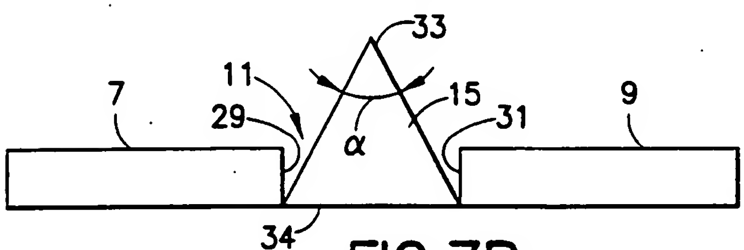

FIG.7B

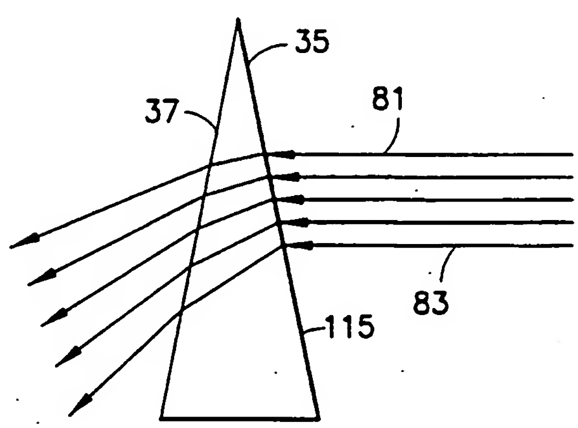

FIG.8

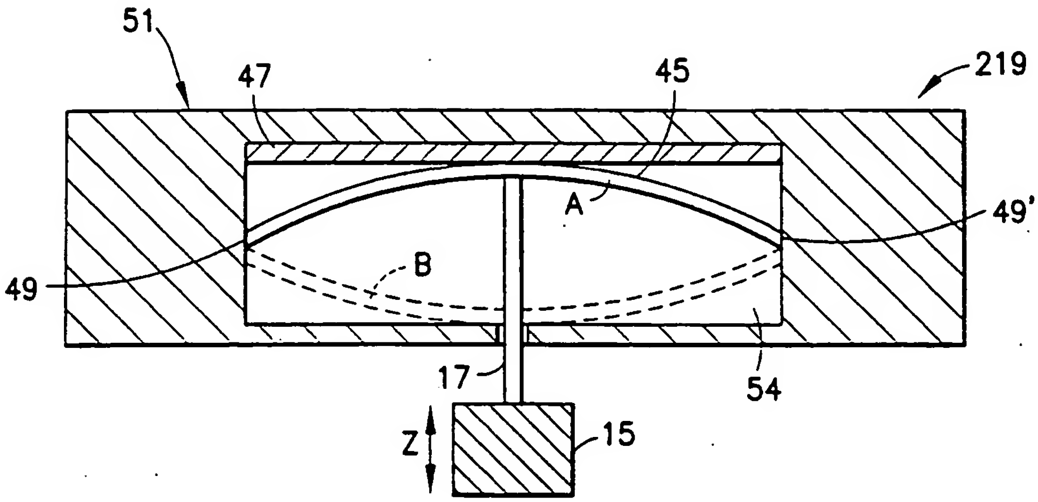

FIG.9

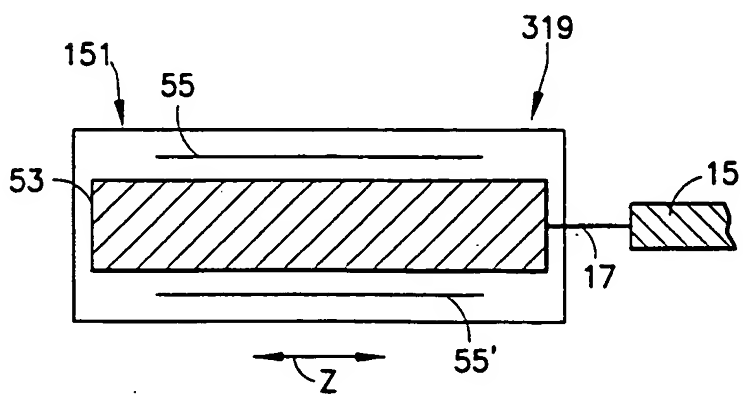

FIG.10

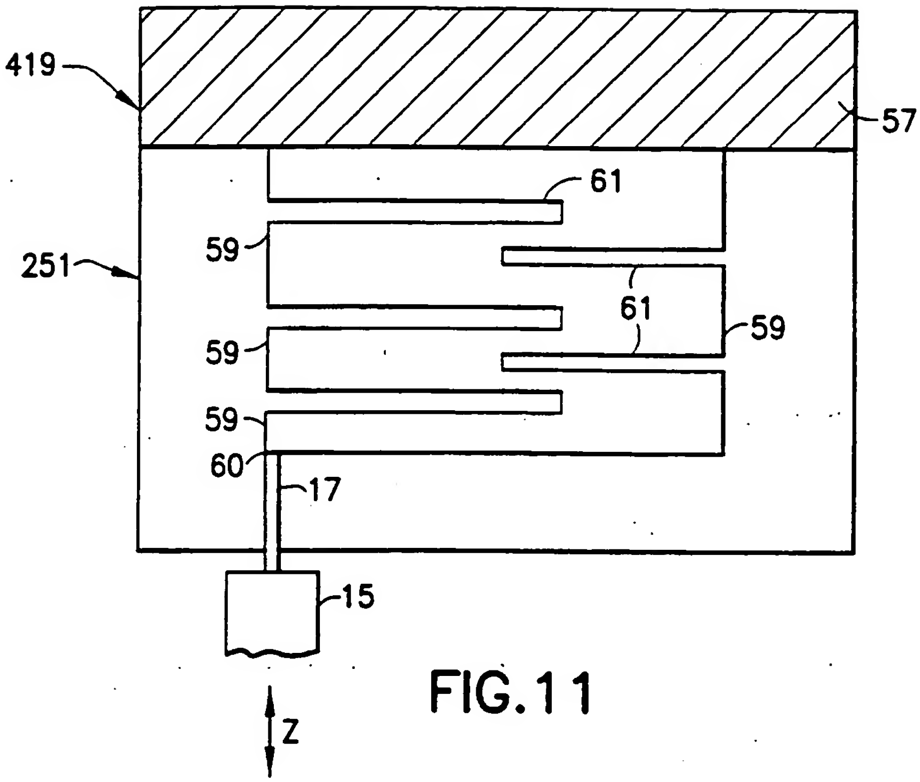

FIG.11

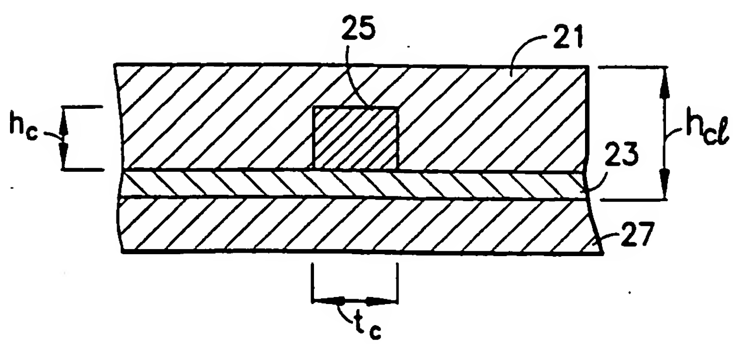

FIG.12

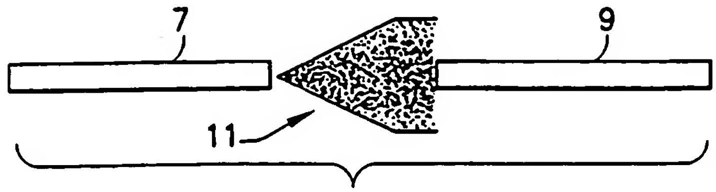

FIG.13A

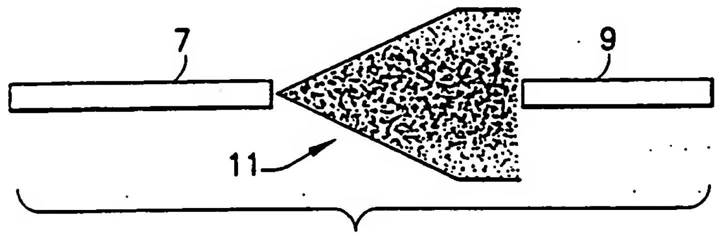

FIG.13B

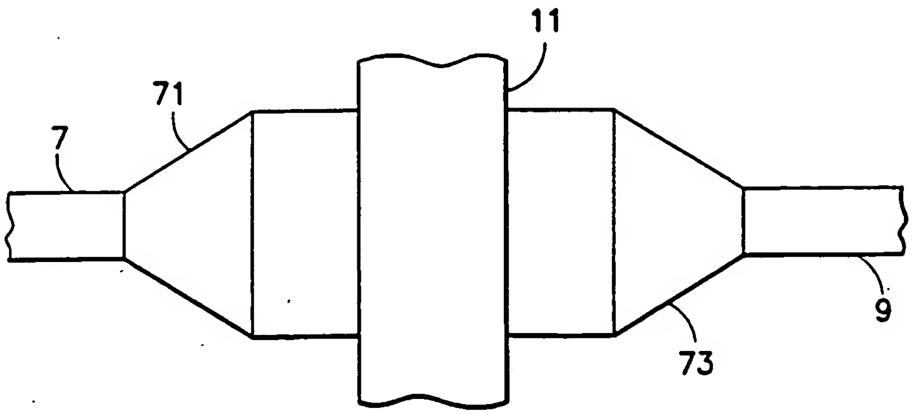

FIG.14

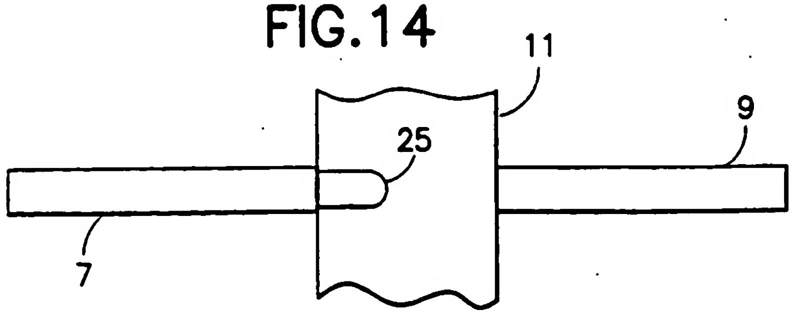

FIG.15

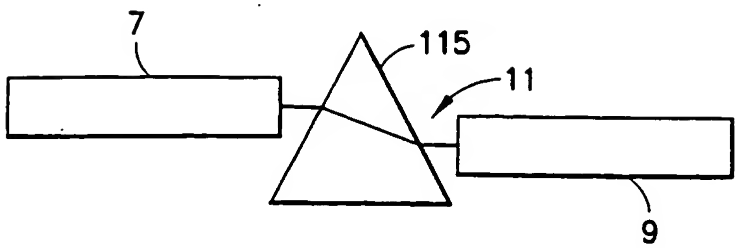

FIG.16

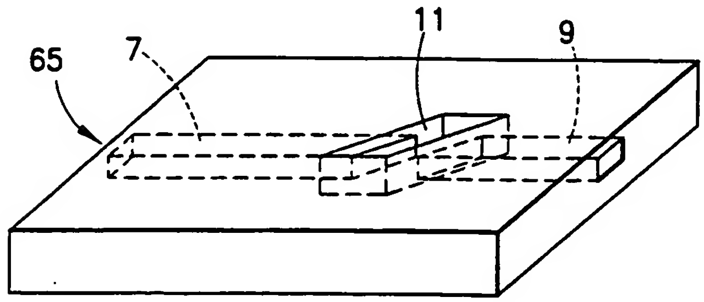

FIG.17A

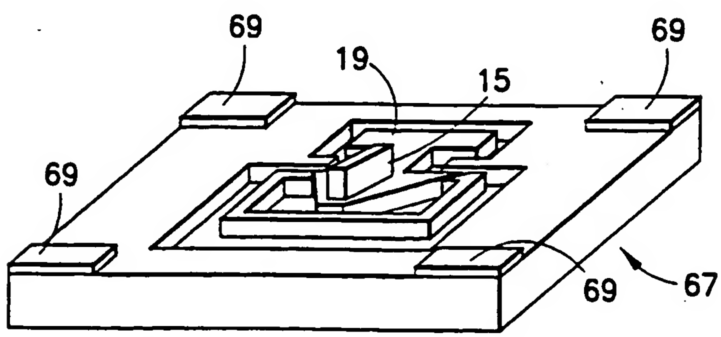

FIG.17B

INTERNATIONAL SEARCH REPORT

Interr ..al Application No
PCT/US 00/32288

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/34 G01J3/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

INSPEC, PAJ, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TIXIER A ET AL: "Microactuated slider-based tunable filters for optical fiber transmission" , 3RD INTERNATIONAL CONFERENCE ON MICRO OPTO ELECTRO MECHANICAL SYSTEMS (OPTICAL MEMS). MOEMS 99. PROCEEDINGS, PROCEEDINGS OF MOEMS 99, MAINZ, GERMANY, 30 AUG.-1 SEPT. 1999 , 1999, MAINZ, GERMANY, INST. MIKROTECHNIK, GERMANY, PAGE(S) 145 - 149 XP000995108	1-6,8-10
Y	the whole document --- -/--	7

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 April 2001	17/04/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lerbinger, K

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INTERNATIONAL SEARCH REPORT

Intern   ...al Application No
PCT/US 00/32288

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GOUY J P ET AL: "Design of a pigtailed tunable filter for optical fiber transmissions at 1.3-1.55 mu m" , DESIGN, TEST, AND MICROFABRICATION OF MEMS AND MOEMS, PARIS, FRANCE, 30 MARCH-1 APRIL 1999 , PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, 1999, SPIE-INT. SOC. OPT. ENG, USA, PAGE(S) 207 - 213 XP000995110 ISSN: 0277-786X	1-6,8-10
Y	the whole document	7
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Information on patent family members

International Application No
PCT/US 00/32288

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